



# RESEARCH MEMORANDUM

MINIMUM SPARK-IGNITION ENERGIES OF 12 PURE FUELS

AT ATMOSPHERIC AND REDUCED PRESSURE

By Allen J. Metzler

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NATIONAL ADVISORY COMMITTEE  
FOR AERONAUTICS

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## SUMMARY

Minimum spark-ignition energies for 12 pure fuels were measured at reduced pressure, and the data obtained were extrapolated to 1 atmosphere. The fuels investigated included normal and cycloparaffins, olefins, carbon disulfide, and oxygenated compounds such as an alcohol, ether, propylene oxide, and tetrahydropyran; these fuels were ignited at reduced pressures by capacitance sparks of controlled duration. The minimum ignition energies obtained are related to the pressure, the quenching distance, and the maximum fundamental flame velocity of the fuel-air mixture. Also, the experimental data obtained are applied to two correlations of spark-ignition energies to check the data of this investigation with that of others.

## INTRODUCTION

The fuels and combustion program of the NACA Lewis laboratory is concerned with those fundamental fuel properties which may affect or ultimately limit the combustion process as it occurs in high-velocity propulsion systems such as ram-jet and turbojet engines. The program includes not only the measurement of fundamental fuel properties but also the evaluation of such properties as reflected in experimental combustor performance.

As a part of the over-all program, it was necessary to obtain consistent minimum-spark-ignition-energy data for a number of pure fuels, some of which were to be investigated in engine combustion chambers. Ignition energies for a number of the fuels are reported in references 1 and 2; however, in most cases, the reported energies are for stoichiometric mixtures only. Values for other fuels were unobtainable. Therefore, consistent data for a variety of fuels were obtained in the present investigation.

The minimum ignition energies for six pure hydrocarbon fuels are reported in reference 3. The results indicated that the minimum ignition energies are proportional to  $1/P^{1.76}$  for all six hydrocarbons, two

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normal paraffins, a cycloparaffin, an olefin, an aromatic, and acetylene. Therefore, it was suspected that this relation might be valid for other hydrocarbon fuels as well as for such fuels as alcohols and ethers.

The work reported herein is an extension of that described in reference 3. Minimum spark-ignition energies are presented for 12 pure fuels; namely, n-pentane, n-heptane, methylcyclohexane, isopentane, pentene-2, acrylonitrile, propylene oxide, tetrahydropyran, 2,2-dimethylbutane, methanol, diethylether, and carbon disulfide. All data were obtained with optimum gap spacing and at reduced pressures no greater than 200 millimeters of mercury absolute by passing a single, fixed-duration spark of 1000 microseconds through a quiescent fuel-air mixture contained in a closed vessel.

The data of this report are compared with those of references 1, 4, and 5. Also, the data are considered in terms of the minimum-spark-ignition-energy correlations developed in these references; to this end, the original reduced-pressure data were extrapolated to atmospheric pressure.

#### EXPERIMENTAL DETAIL

##### Apparatus

The apparatus used for this investigation consisted of a constant-temperature enclosure containing a vapor-air mixing system and an ignition bomb, a power supply, and an energy-measuring circuit.

The inlet and mixing system as shown in figure 1 provided for the handling of either gaseous or liquid fuels. Gaseous fuels were admitted directly from a tank supply, while liquid fuels were admitted from thimble E after freezing. The size of the liquid samples was so adjusted that the entire sample, when evaporated and mixed with sufficient air, formed the desired fuel-air mixture. Measured quantities of fuel vapor and air, from a compressed-air cylinder, were thoroughly mixed in tank C by means of a motor-driven bellows-sealed mixer prior to admission to the ignition bomb. An air thermostat controlled the system temperature to  $100^{\circ} \pm 2^{\circ}$  F.

The ignition bomb (fig. 2) had a total volume of approximately 680 cubic centimeters and was of stainless-steel construction. An iron-constantan thermocouple inserted through the bomb base measured the mixture temperature. Lucite windows were used for observation, and a single quartz window was located at the top of the bomb to permit ultra-violet irradiation of the electrode gap to control gap breakdown potential. The electrodes were number 74 high-speed drills (0.0225 inch in diam.) for all fuels except carbon disulfide for which 3/8-inch-diameter lead spheres

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were used. A 1-inch Lucite rod insulated the electrodes, and a greased O-ring provided a vacuum tight, sliding seal to facilitate setting the gap width, which was measured directly with an integrally mounted micrometer screw.

The electric circuit associated with this equipment is schematically shown in figure 3. The 0.6-microfarad condenser bank was charged by a fully variable 0- to 30-kilovolt power supply; the condenser voltage was measured by a 0- to 20-kilovolt electrostatic voltmeter. Isolation of the power supply from the discharge circuit was accomplished with switch B, a single-pole double-throw magnetically operated air switch, as shown in figure 3; thus, any power-supply leakage to the condenser bank was eliminated for the duration of the discharge. Circuit resistances  $R_1$  and  $R_2$  fixed the circuit discharge characteristics, while  $R_3$  was the known resistance for measurement of the gap current. Shunt resistance  $R_1$  was fixed at approximately 500 ohms to give a total discharge duration of 1000 microseconds;  $R_2$  together with condenser voltage was varied to impress an energy pulse of known duration across the electrode gap. Gap voltages, however, were not impressed directly upon the oscilloscope but were reduced by a combination capacitor-resistor voltage divider, balanced with respect to ground potential. The divider was balanced to  $\pm 0.8$  percent over a frequency range of 60 cycles per second to 70 kilocycles per second and was checked to  $\pm 1.4$  percent by a discharge of a known voltage through a fixed circuit.

The over-all circuit and oscilloscope capacitance characteristics fixed a minimum energy of approximately 1 millijoule. For lower energies, spark reproducibility and energy-measurement accuracy decrease; the investigation was therefore limited to pressures no greater than 200 millimeters absolute in order consistently to exceed this energy limit.

### Procedure

Fuel-air ratios were obtained volumetrically by measurement of the partial pressures of the fuel and the air in the mixing tank, and all data were obtained for premixed fuel-air mixtures of known concentration, temperature, and pressure. The minimum spark-ignition energy for such known conditions and a given gap width was approached from the low side by passing consecutive sparks and adjusting the capacitor voltage,  $R_2$ , and  $R_3$ . Ignition of the mixture was defined as the occurrence of flame propagation from the spark source into the surrounding gas to an extent sufficient to yield either a 5-millimeter-pressure pulse in the system or a visible flash throughout the volume. The magnitude of the energy expended in this spark was calculated, as described in reference 6, from the oscillographic record of the instantaneous voltages across  $R_3$  and

across the electrode gap. For all data reported, ignition was obtained from a single spark in a mixture not previously sparked. The energy so determined for a given mixture and various gap widths defined the minimum spark-ignition energy for that mixture. Repeating the procedure for various mixture strengths defined the minimum ignition energy as a function of fuel-air ratio or the equivalence ratio. All data are reported on this basis.

Experimental conditions produced a glow type of spark discharge almost exclusively, its duration being about 1000 microseconds. Deviations in total spark duration, however, introduced negligible error, since 90 percent of the total energy was released in the first 50 percent of the spark time. The data for all fuels except carbon disulfide were obtained using needle-type electrodes; carbon disulfide, however, required the use of 3/8-inch lead spheres to overcome severe arc-to-glow oscillations of the discharge. Although these oscillations may have arisen from effects of the electrode material, it seems more probable that they resulted from insufficient electrode surface area for charge accommodation.

Data for all fuels except carbon disulfide were obtained at pressures of 100 or 200 millimeters of mercury absolute or both. Data for carbon disulfide were obtained at a pressure of 27.8 millimeters of mercury absolute in order to obtain a well defined glow discharge, since higher pressures resulted in severe discharge oscillations. However, a single datum point at 12.5 millimeters was also obtained although oscillations were sufficiently severe to reduce the accuracy of this point.

#### Limits and Accuracy

All data reported herein are, of course, subject to certain experimental limits and accuracies. The original data for all fuels investigated were obtained at 100° F and at pressures of 200 millimeters of mercury absolute and below. Except for a single point for carbon disulfide, all data presented are considered accurate to  $\pm 8$  percent. This figure was estimated from the accuracies of the calibration of individual circuit components plus an additional allowance for spark reproducibility. Data reproducibility, however, is within  $\pm 5$  percent.

The fuels investigated and the source and purity of each are listed in table I.

#### RESULTS OF INVESTIGATION

In this paper  $H'$  denotes the minimum ignition energy at the lowest point on the ignition-energy - equivalence-ratio curve,  $H_{\phi}$  denotes the

minimum ignition energy at any point on the curve other than the lowest point  $H'$ , and  $\phi$  denotes the equivalence ratio under consideration and is defined as the ratio of the actual fuel-air ratio to that at stoichiometric conditions. Rich mixtures therefore exhibit values of  $\phi$  greater than 1.0.

#### Reduced-Pressure Data

The experimental data for the 12 fuels investigated are plotted in figures 4 to 7 as ignition-energy against equivalence-ratio and are individually tabulated in table II. Figure 4 contains the paraffinic and cycloparaffinic data; figure 5, olefinic data; figure 6, data for oxygenated fuels; and figure 7, carbon disulfide data. It should be noted that, in these figures, points separated by less than  $0.1\phi$  are check points that were not run on the same day or with the same initial mixture. Comparison of such points will illustrate the reproducibility of these data.

Minimum-ignition-energy data for all fuels were obtained at reduced pressures no greater than 200 millimeters of mercury absolute and at optimum gap spacing. Since all data exhibited rather flat energy-gap curves as a result of the low quenching effect of the needle electrodes, the quenching distance  $d$  was not sharply defined; but all quenching distances as measured and reported in table II occurred within the limits reported in reference 5, approximately  $\pm 25$  percent of a mean. Except for differences in general energy level, the most marked difference between fuels is the shift of  $H'$  with respect to  $\phi$  as indicated by figures 4(a) and 4(b) which show a shift of  $H'$  from  $\phi = 1.35$  for n-pentane to  $\phi = 1.75$  for n-heptane. As a result of this shift, normal paraffins which exhibit similar values of  $H'$  may have values of  $H_{1.0}$  (minimum spark-ignition energy at an equivalence ratio of 1.0) that vary by as much as a factor of 4. The need for exact definition of the bases of fuel comparisons is immediately apparent. Data for  $H'$  at the experimental pressures  $P$  and for the pressure exponent in the relation  $H' \propto 1/P^x$  are tabulated in table III for all the fuels of this investigation.

#### Data Extrapolated to 760 Millimeters of Mercury Absolute

Although the original experimental data were obtained at reduced pressures, extrapolation of the experimental data to 1 atmosphere was desirable, because it permitted comparison with the data of other investigators as reported in the literature (refs. 2 and 4). For all fuels for which data were obtained at two pressures, the  $H'$  at 1 atmosphere was obtained by extrapolation of the reduced-pressure data to 760 millimeters using the slopes indicated in table III. The 200-millimeter  $H'$

data of the remaining three fuels and the 100-millimeter  $H'$  data of acrylonitrile were extrapolated by using the pressure relation established in reference 3, namely  $H' \propto \frac{1}{p^{1.76}}$ . The extrapolated values of  $H'$  for 1 atmosphere are tabulated in table IV together with other available data for comparison.

The accuracy of the extrapolation of carbon disulfide data is probably low since (1) in the extrapolation, an exponential  $H'$ -pressure relation to pressures as low as 12 millimeters of mercury absolute is assumed, and (2) the accuracy of the extrapolation hinges on the questionable accuracy of the single point at 12.5 millimeters. However, the correct value of  $H'$  for carbon disulfide as determined in this investigation is estimated to be somewhere between 0.02 and 0.03 millijoule. A more complete pressure study is necessary to verify the initial assumption and to fix more accurately the value of  $H'$ .

Atmospheric pressure values for  $H_{1.0}$  are obtained from the extrapolated  $H'$  values by assuming

$$\left( \frac{H_{1.0}}{H'} \right)_{200 \text{ mm}} = \left( \frac{H_{1.0}}{H'} \right)_{760 \text{ mm}}$$

The atmospheric data for  $H_{1.0}$  obtained in this way are compared with those of reference 2 in table V.

## DISCUSSION

### General Trends

The data of this investigation and that of reference 3 reveal certain general trends which are effects not of the apparatus but rather of the fuel type upon the minimum spark-ignition energy. Exceptions to the following trends can be found, but, in general: (1) The minimum spark-ignition energy  $H'$  of all paraffins and cycloparaffins is approximately the same from  $C_2$  to at least  $C_7$ . (2) Unsaturation in a carbon chain lowers the ignition energy, but unsaturation in a ring structure (benzene) has relatively little effect on this energy.

These relations are the same as those found in reference 2, where the effect of molecular structure upon the ignition energy at stoichiometric conditions was investigated. However, in reference 2, it is reported that ignition energy increases with increasing paraffinic chain length. This is true for the case considered,  $H_{1.0}$ , but is the result of the shift of  $\phi$  at  $H'$  to higher values as paraffinic chain length increases.

Correlation of  $H'$  With Lean-Limit Flame Temperature

In the present report and in reference 3, consistent minimum-ignition-energy data for 18 fuels having a variety of structures are reported, and it is of interest to know whether these data fit correlations which have been previously proposed.

In reference 1, the minimum spark-ignition energy, the lean-limit flame temperature, and the energy of activation of the combustion reaction are correlated. The relation which was developed and which may be checked experimentally is given in the following equation:

$$\log \frac{HN_0^{3/2}}{T_f - T_0} = L + 2 \log T_0 - 2 \log P_0 + \frac{0.65 \alpha T_f(\text{lean})}{RT_f} \quad (1)$$

where

$H$  minimum ignition energy, joules

$N_0$  mole fraction of oxygen

$T_f$  flame temperature,  $^{\circ}\text{K}$

$T_0$  initial mixture temperature,  $^{\circ}\text{K}$

$P_0$  initial mixture pressure, atm

$R$  gas constant, 1.98 cal/(mole)(deg)

$\alpha, L$  constants

The data reported herein and in reference 3 were applied by suitable substitution in equation (1). Flame temperatures at stoichiometric and at the lean limit were obtained from reference 1, and a correlation between

$\log \frac{HN_0^{3/2}}{T_f - T_0}$  and  $\frac{T_f(\text{lean})}{T_f}$  was attempted. As shown by figure 8,

a reasonably good correlation between the temperature ratio and the minimum ignition energy for stoichiometric  $H_{1.0}$  exists. The solid line was computed by the method of least squares for the data points shown and evaluates  $\alpha$  at about 20.4. The data of reference 1 are represented by the dashed line.

Since it is desirable to be able to predict  $H'$ , an attempt was made to correlate  $H'$  by using  $N_0$  at  $\phi_{\min}$ , and  $T_f$  at  $\phi_{\min}$ . The flame temperature at  $\phi_{\min}$ , the equivalence ratio at  $H'$ , was calculated by the



method given in reference 7. No correlation resulted except for those fuels where  $\phi_{\min}$  was nearly equal to 1 or less than 1. It appears then that the correlation is limited to a maximum equivalence ratio of approximately 1.0 and that this limit is undoubtedly imposed by some of the initial assumptions made in reference 1 involving  $T_f$  and  $T_f - T_0$ .

The correlation also predicts an inverse relation of the minimum ignition energy to the square of the pressure. This relation is in reasonable agreement with the data reported in table III and in reference 3. The pressure exponent varied from -1.65 to -2.00, the mean value being -1.82. The agreement indicates a relative insensitivity to  $\phi$  since the experimental data cover a range of  $\phi$  from 0.8 to approximately 1.8.

#### Correlation of $H'$ and Flame Velocity

The correlation of the maximum fundamental flame velocity  $U_{f,\max}$  with the minimum spark-ignition energy  $H'$  at 1 atmosphere was again checked in this investigation. This correlation is presented in reference 3 for 13 fuels for which values of  $H'$  were available; the relation between these two properties was  $U_{f,\max} \propto \frac{1}{(H')^{0.8}}$ . The results of the present investigation together with data from reference 3 are plotted in figure 9. Where possible, flame velocities from references 8 to 10 were used, but where flame velocities of reference 11 were used, they were first adjusted to the data of reference 8. Carbon disulfide is included in the plot, but it is obvious why it was not considered in the correlation. The least-squares method as applied to the data of figure 9 gives  $U_{f,\max} \propto \frac{1}{(H')^{0.83}}$ . Additional data in the low-energy region are required to accurately fix an exponent for  $H'$ ; yet, on the basis of the present data, a definite relation between these two fundamental properties does appear to exist; that is, for all practical purposes

$$U_{f,\max} \propto \frac{1}{(H')^{0.8}}$$

#### Correlation of $H'$ with Quenching Distance

The measured minimum ignition energy is plotted as a function of the optimum gap spacing, or quenching distance, in figure 10. Minimum ignition energies, both  $H_{1.0}$  and  $H'$ , and associated quenching distances as experimentally determined are plotted in the figure. The solid line is the least-squares representation of all the data, and the equation for this line is

$$H = 6.36 d^{1.79}$$

Also shown in figure 10 are curves representing the data of references 2 and 5; the data of reference 5 is in fair agreement with the data reported herein. Quenching distances at an equivalence ratio of 1 and atmospheric pressure were obtained by use of the solid line in figure 10 and the extrapolated values of  $H_{1.0}$ . These extrapolated quenching distances are compared with the data of reference 2 in table V and are seen to be consistently lower than the data of reference 2 although the values are in fair agreement.

#### Application of Data to Theory of Excess Enthalpy

In reference 5, the minimum ignition energy is related to quenching distance, flame speed, and  $T_f - T_0$  by the following equation:

$$H = \frac{\pi\mu}{u_f} d^2 \Delta T \quad (2)$$

where the excess enthalpy is equal to the minimum ignition energy  $H$  in calories,  $u_f$  is the flame velocity of the mixture in centimeters per second,  $d$  is the quenching distance in centimeters,  $\Delta T = T_f - T_0$  in  $^{\circ}\text{C}$ , and  $\mu$  is the heat conductivity of the mixture in calories per centimeter per second per  $^{\circ}\text{C}$ . The data of the present investigation were considered in the light of the relations expressed in equation (2) and were applied to the equation by substitution of the extrapolated quenching distances from table V. Also, for these calculations  $u_f$  and  $T_f$  were obtained from references 1, 8, and 10; and  $\mu$  was assumed to be  $6.3 \times 10^{-5}$ . The results of these calculations are tabulated in table VI. In all cases, calculated energies are greater than those extrapolated from experimental data. The data for the ratio of the calculated ignition energy to the extrapolated values are in fair agreement with those reported in reference 12; that is, 2, 4, and 6 for stoichiometric fuel-air mixtures of hydrogen, propane, and methane, respectively. It appears then that although the data exhibit good correlation with theory, the prediction of absolute values of ignition energy from equation (2) requires an additional empirical factor. This factor must necessarily be a function of  $\phi$  since reference 12 indicates a rapid departure of the calculated values from experimental values as dilution of the combustible with either fuel or air is increased.

## SUMMARY OF RESULTS

The following results were obtained in an investigation of the minimum spark-ignition energies of 12 pure fuels, namely: n-pentane, n-heptane, methylcyclohexane, isopentane, pentene-2, acrylonitrile, 2,2-dimethylbutane, diethylether, methanol, propylene oxide, tetrahydropyran, and carbon disulfide. The results apply to the lowest point ( $H'$ ) on the minimum spark-ignition energy against equivalence ratio ( $\phi$ ) curve and do not necessarily apply to minimum energies at other points on the curve.

1. All paraffins and cycloparaffins including the branched members of the group had essentially the same minimum spark-ignition energies.

2. Unsaturation in a carbon chain markedly lowered the minimum ignition energy; the extent of the decrease appeared to be dependent upon the individual compound; for example, the ignition energy for ethylene was lower than that of pentene-2.

3. Unsaturation in a ring structure such as benzene was relatively ineffective in decreasing the minimum ignition energy from that of the equivalent paraffinic or cycloparaffinic structures.

4. The ignition energies of oxygenated fuels, such as oxides and alcohols, exhibited no definite trend.

5. The equivalence ratio at which the minimum ignition energy  $H'$  occurred was determined by the length of the carbon chain and was relatively insensitive to pressure.

6. The pressure exponent in  $H' \propto \frac{1}{p^x}$  was constant at about 1.82 for most fuels investigated; the maximum variation was from 1.65 to 2.00.

7. The relation between the flame velocity and the ignition energy for all fuels investigated except carbon disulfide could be represented by  $U_f(\max) \propto \frac{1}{(H')^{0.8}}$ .

8. The relation between the minimum ignition energy and the quenching distance could be reasonably well represented by  $H_\phi = 6.36 d^{1.79}$  for all fuels investigated.

Lewis Flight Propulsion Laboratory  
National Advisory Committee for Aeronautics  
Cleveland, Ohio, August 31, 1953

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TABLE I. - SOURCE AND PURITY OF FUELS INVESTIGATED

Fuel	Source	Purity, percent (a)
n-Pentane	Phillips Petroleum Co.	99+
n-Heptane	Phillips Petroleum Co.	99+
Methylcyclohexane	Phillips Petroleum Co.	99+
Isopentane	Phillips Petroleum Co.	99+
Pentene-2	National Bureau of Standards	99+
Acrylonitrile	Monsanto Chemical Co.	95+
2,2-Dimethylbutane	Phillips Petroleum Co.	99+
Diethylether	Mallinckrodt Chemical Works	99+
Methanol	J. T. Baker Chemical Co.	99+
Propylene oxide	Eastman Kodak Company	99+
Tetrahydropyran	E. I. DuPont	95
Carbon disulfide	Mallinckrodt Chemical Works	99+

<sup>a</sup>Purity of tetrahydropyran and acrylonitrile, estimated;  
purity of other fuels, stated by manufacturer.



TABLE II. - MINIMUM SPARK-IGNITION ENERGIES AND QUENCHING DISTANCES FOR 12 PURE FUELS AT REDUCED PRESSURE

Equiva- lence ratio, $\phi$	Pressure, P, mm Hg abs	Minimum spark- ignition energy, E <sub>sp</sub> , milli- joules	Quenching distance, d, cm	Equiva- lence ratio, $\phi$	Pressure, P, mm Hg abs	Minimum spark- ignition energy, E <sub>sp</sub> , milli- joules	Quenching distance, d, cm	Equiva- lence ratio, $\phi$	Pressure, P, mm Hg abs	Minimum spark- ignition energy, E <sub>sp</sub> , milli- joules	Quenching distance, d, cm
n-Pentane				Isopentane				Diethylether			
2.04	200	3.8	0.86	2.05	100	13.7	1.30	1.88	200	3.1	0.61
1.85		3.1	.78	1.86		10.1	1.27	1.82		3.0	.48
1.31		2.3	.53	1.64		9.0	1.14	1.82		2.6	.48
1.31		2.3	.61	1.31		8.9	1.27	1.82		2.6	.48
1.01		3.5	.74	1.00		12.2	1.65	1.32		2.7	.46
1.02		3.5	.89					1.32		2.8	.46
n-Heptane				Pentene-2							
2.01	200	3.2	0.89	1.84	200	2.6	0.51	.98	100	3.6	.71
1.93		2.8	.68	1.82		2.2	.63	.88		3.5	.61
1.75		2.2	.51	1.31		2.6	.64	1.86		8.9	1.02
1.61		2.6	.53	1.00		3.3	.98	1.83		8.0	1.20
1.57		2.4	.53	1.84		11.7	1.07	1.32		8.5	1.42
1.37		3.4	.89	1.84	100	10.2	1.42	.99		10.9	1.73
1.01		5.0	.97	1.63		8.6	1.07	.98		12.0	1.38
.98		5.4	.81	1.31		9.9	1.22				
Methylcyclohexane				1.30		8.4	1.17	Propylene oxide			
				1.00		14.1	1.67	1.87	200	1.9	0.48
				Methanol				1.84		2.2	.41
2.05	200	4.0	0.61	1.74	200	3.9	0.84	1.84		1.8	.48
1.85		2.8	.53	1.48		2.3	.48	1.82		1.9	.38
1.62		2.9	.64	1.42		2.2	.58	1.46		1.7	.45
1.42		3.3	.74	1.25		2.0	.48	1.32		1.6	.38
1.35		3.4	.89	1.00		2.5	.53	1.31	1.6	.31	
1.01		5.4	1.22	.84	100	3.2	.81	.99	1.8	.58	
1.00		5.5	1.11	1.74		17.6	2.00	1.84	7.5	.73	
2,2-Dimethylbutane				1.68		15.2	1.22	1.63	5.9	.73	
				1.35		8.3	1.06	1.61	5.9	.88	
1.83	200	3.3	0.59	1.00		9.9	1.37	1.31	6.3	.76	
1.63		2.8	.58	.84		12.0	1.46	.99		6.5	.89
1.56		2.8	.69	Carbon disulfide				Tetrahydropyran			
.89		5.6	.99	1.83	27.8	10.5	1.19	1.87	200	2.8	0.61
1.83	100	11.9	1.58	1.44		9.9	1.09	1.74		2.3	.46
1.63		9.4	1.66	1.21		10.5	1.19	1.60		2.4	.48
1.38		11.3	1.27	.99		10.8	1.29	1.43		2.4	.41
.99		16.3	1.93	1.44		40.6	2.08	1.30		2.7	.41
Isopentane				Acrylonitrile				1.81	100	8.7	1.27
2.08	200	3.7	0.89	1.29	100	7.3	0.97	1.74		8.4	.94
2.05		3.5	.61	1.54		8.0	.91	1.60		7.8	.91
1.86		2.5	.58	1.79		5.8	.97	1.43		8.8	1.02
1.64		2.5	.81	2.08		8.8	1.09	1.30		9.0	1.22
1.31		2.5	.71					1.20		10.4	1.27
1.01		3.6	.84								
1.00		4.1	.71								

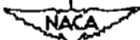




TABLE III. - MINIMUM SPARK-IGNITION ENERGIES AT REDUCED PRESSURE

Fuel	Pressure, P, mm Hg	Equiva- lence ratio, $\phi_{min}$	Minimum spark- ignition energy, H', millijoules	Slope, $\log H'/P$
n-Pentane	200	1.35	2.2	-----
n-Heptane	200	1.75	2.4	-----
Methylcyclohexane	200	1.80	2.7	-----
2,2-Dimethylbutane	200	1.55	2.7	-1.78
	100	1.65	9.4	-----
Isopentane	200	1.55	2.4	-1.84
	100	1.45	8.6	-----
Pentene-2	200	1.60	2.2	-1.95
	100	1.60	8.5	-----
Acrylonitrile	100	1.70	5.8	-----
Methanol	200	1.25	2.0	-2.00
	100	1.25	8.0	-----
Diethylether	200	1.55	2.5	-1.65
	100	1.55	8.0	-----
Propylene oxide	200	1.30	1.6	-1.83
	100	1.50	5.7	-----
Tetrahydropyran	200	1.60	2.2	-1.76
	100	1.55	7.8	-----
Carbon disulfide	27.8	1.35	9.9	-1.76
	12.5	-----	$\approx 41$	-----

TABLE IV. - MINIMUM SPARK-IGNITION ENERGIES EXTRAPOLATED  
TO ATMOSPHERIC PRESSURE

Fuel	Minimum spark-ignition energy H', millijoules		
	Reference 4	Reference 2	Extrapolated data
n-Pentane	0.25	0.28	0.22
n-Heptane	.25		.24
Methylcyclohexane			.27
Isopentane			.21
Pentene-2			.18
Acrylonitrile			.16
2,2-Methylbutane			.25
Diethylether	.19		.28
Methanol			.14
Propylene oxide		.13	.14
Tetrahydropyran			.22
Carbon disulfide		.009	.03



TABLE V. - COMPARISON OF MINIMUM SPARK-IGNITION ENERGIES AND QUENCHING DISTANCES AT EQUIVALENCE RATIO OF 1.0 EXTRAPOLATED TO ATMOSPHERIC PRESSURE

Fuel	Minimum spark-ignition energy, $H_{1.0}$ , millijoules		Quenching distance, d, cm	
	Extrapolated data	Reference 2	Extrapolated data	Reference 2
Ethane	0.25	0.285	0.17	-----
n-Pentane	.34	.49	.20	0.24
n-Hexane	.50	-----	.24	-----
n-Heptane	.50	.70	.24	.25
Isopentane	.34	.70	.20	.22
2,2-Dimethylbutane	.59	1.64	.27	.23
Cyclohexane	.37	1.38	.21	.25
Methylcyclohexane	.53	-----	.25	-----
Benzene	.40	.55	.22	.20
Ethylene	.12	.096	.11	.11
Pentene-2	.27	.47	.17	.215
Acrylonitrile	.36	-----	.20	-----
Acetylene	.058	.02	.073	.077
Methanol	.18	.215	.14	.15
Diethylether	.39	.49	.21	.235
Propylene oxide	.16	.19	.13	.155
Tetrahydropyran	.49	1.21	.24	.29
Carbon disulfide	.033	.015	.053	.07

TABLE VI. - COMPARISON OF EXTRAPOLATED AND CALCULATED VALUES OF MINIMUM SPARK-IGNITION ENERGY AT ATMOSPHERIC PRESSURE AND EQUIVALENCE RATIO OF 1.0

Fuel	Minimum spark-ignition energy, $H_{1.0}$ , joules $\times 10^5$		$\frac{H_{calc}}{H_{ext}}$
	Calculated	Extrapolated	
Ethane	101.6	25	4.1
n-Pentane	155.6	34	4.6
n-Hexane	238.0	50	4.8
n-Heptane	224.2	50	4.5
Isopentane	170.0	34	5.0
2,2-Dimethylbutane	349.0	59	5.9
Cyclohexane	173.6	37	4.7
Benzene	182.0	40	4.6
Ethylene	27.6	12	2.3
Pentene-2	98.3	27	3.6
Acrylonitrile	127.6	36	3.6
Acetylene	7.1	5.8	1.2
Methanol	51.8	18	2.8
Diethylether	146.5	39	3.7
Propylene oxide	42.2	16	2.6
Tetrahydropyran	182.8	49	3.7
Carbon disulfide	7.6	3.3	2.3



- A Constant-temperature enclosure
- B Vacuum indicators
- C Mixing tank
- D Ignition bomb
- E Thimble for liquid samples
- F Air heater and circulating fan for temperature control

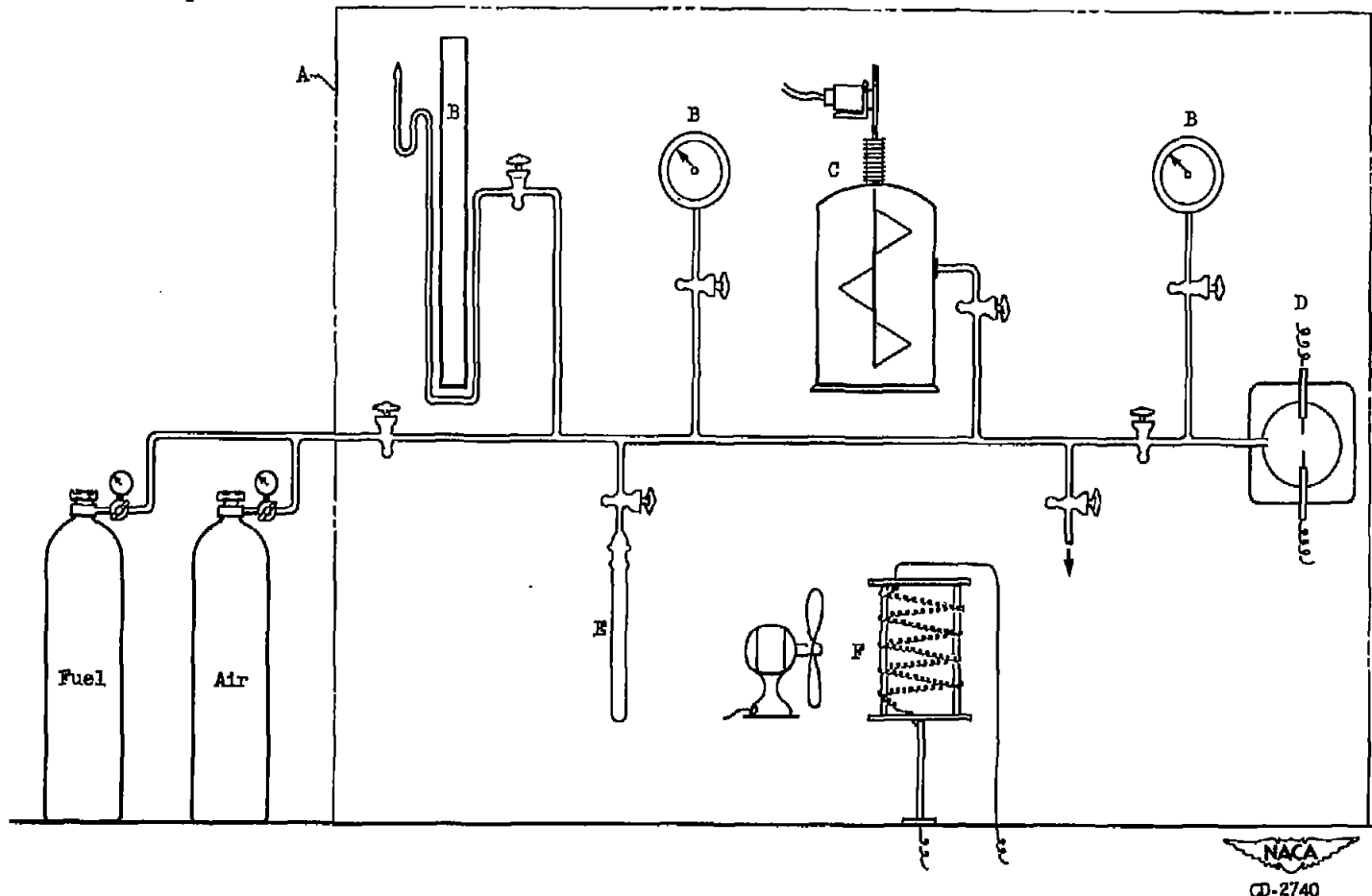


Figure 1. - Schematic diagram of inlet and mixing system for ignition apparatus.

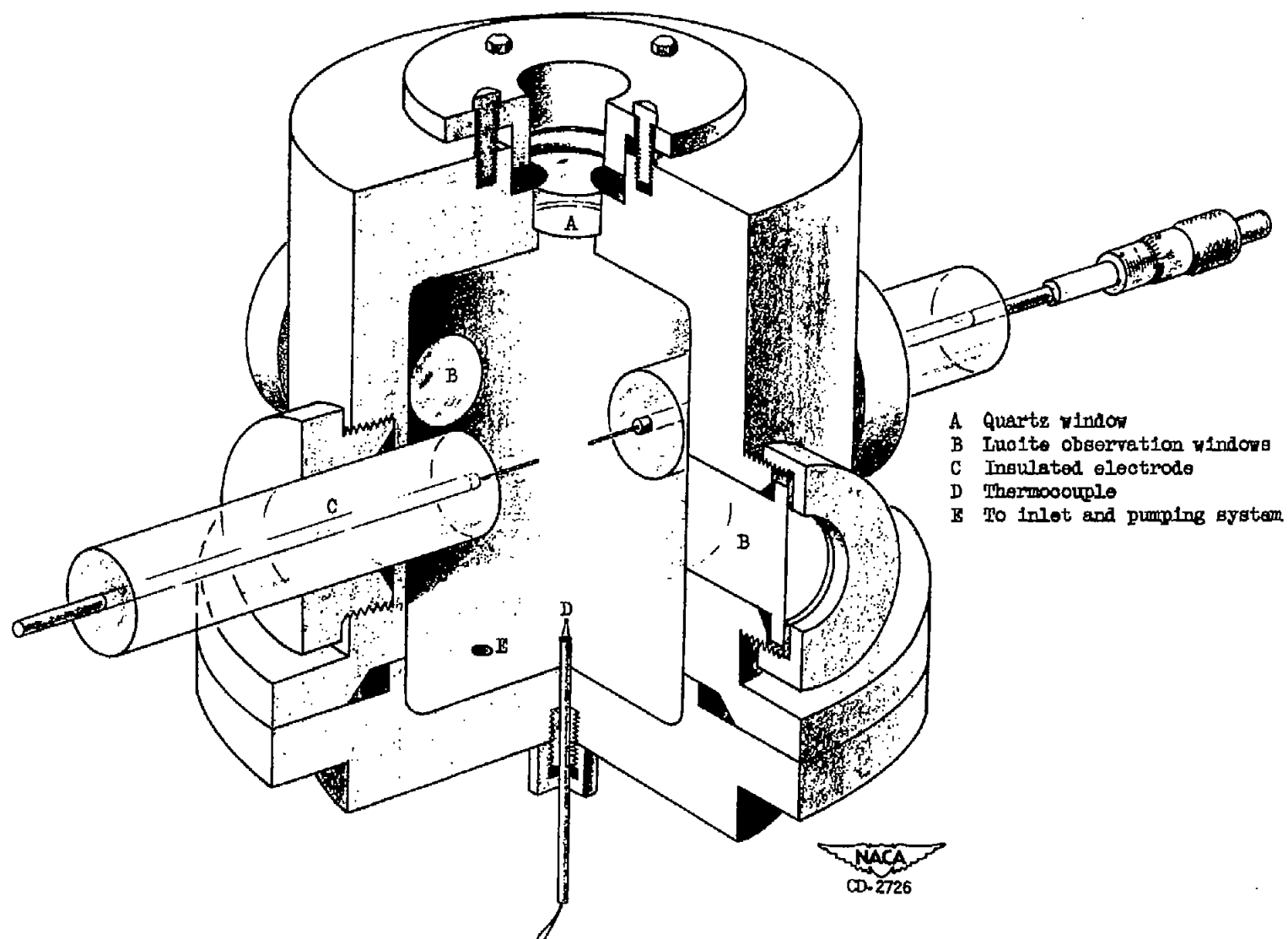


Figure 2. - Ignition bomb, showing electrode and window positions.

- |   |   |       |   |
|---|---|-------|---|
| A | 30-Kilovolt power supply                                | H     | Audio oscillator                                |
| B | Single-pole double-throw air switch                     | $R_1$ | Fixed resistance, 500 ohms                      |
| C | Oscilloscope  | $R_2$ | Variable resistance, 10,000 ohms to 0.50 megohm |
| D | Capacitor bank - six 4-microfarad, 2500-volt capacitors | $R_3$ | Variable resistance, 1000 to 13,000 ohms        |
| E | Ignition bomb   | V     | Electrostatic voltmeter                         |
| F | z-axis input  |       |   |
| G | Voltage divider (approximate reduction, 5:1)            |       |   |

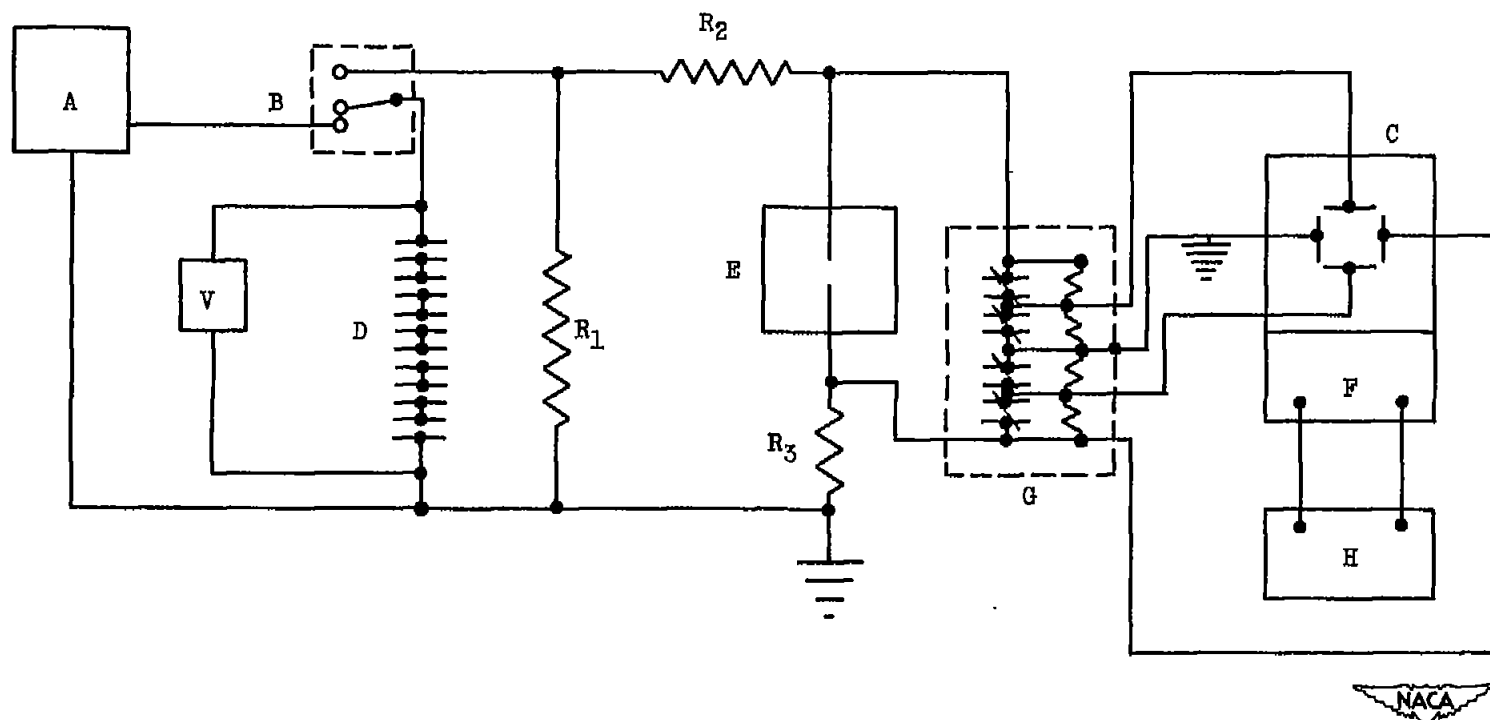


Figure 3. - Schematic diagram of ignition and energy-measuring circuit.

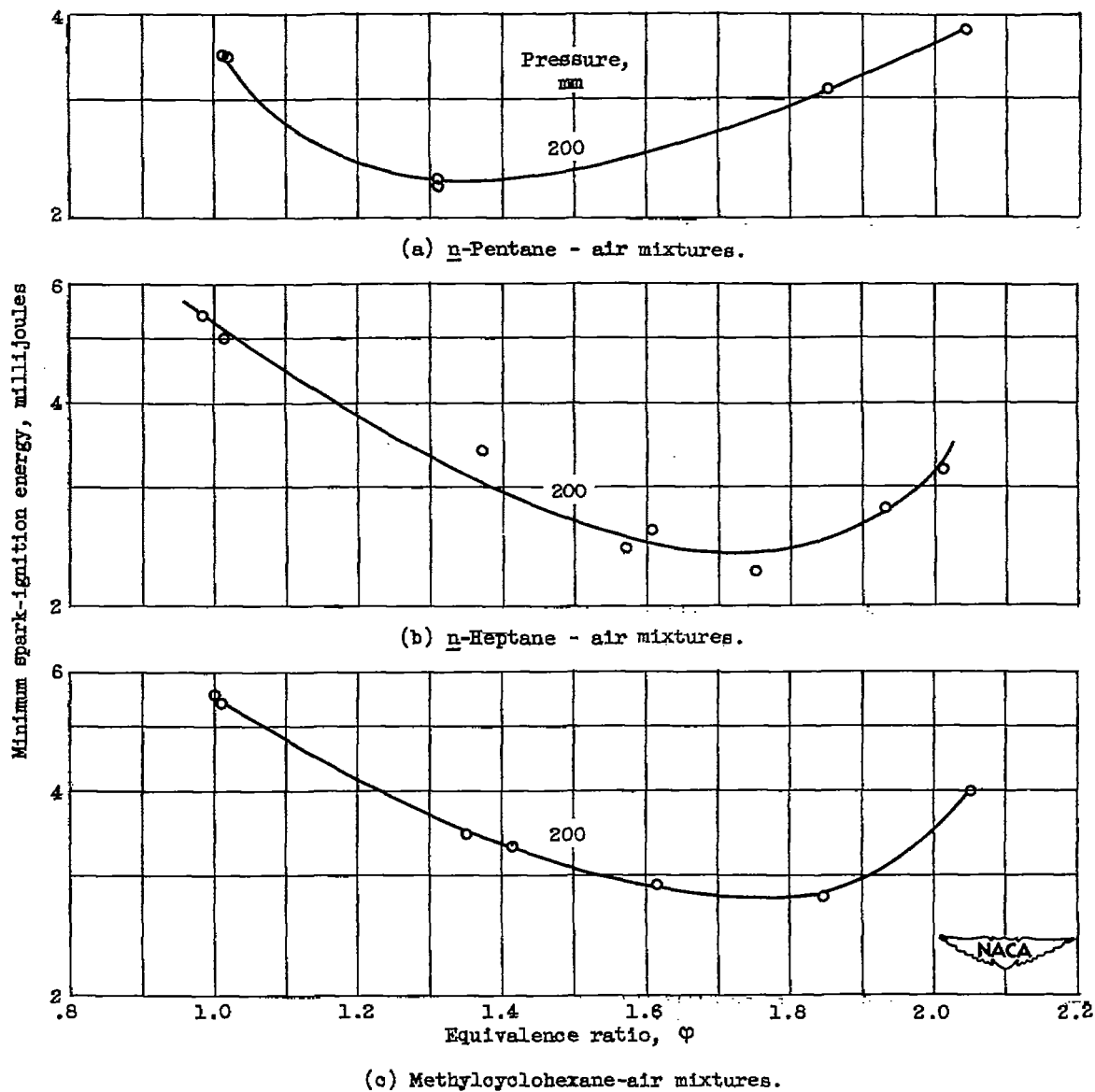
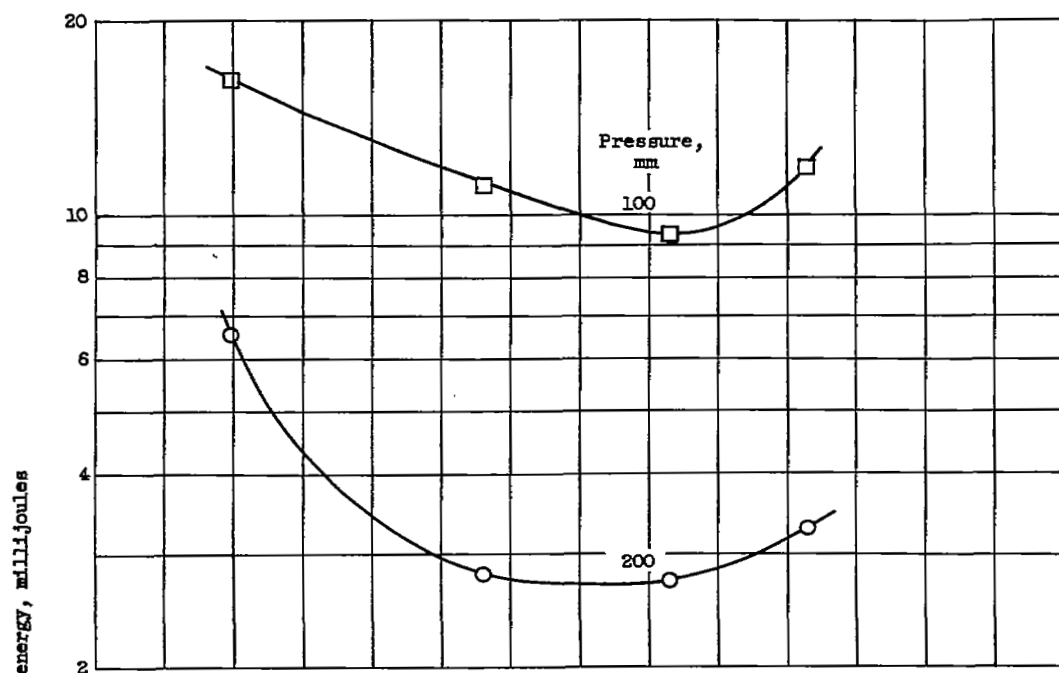
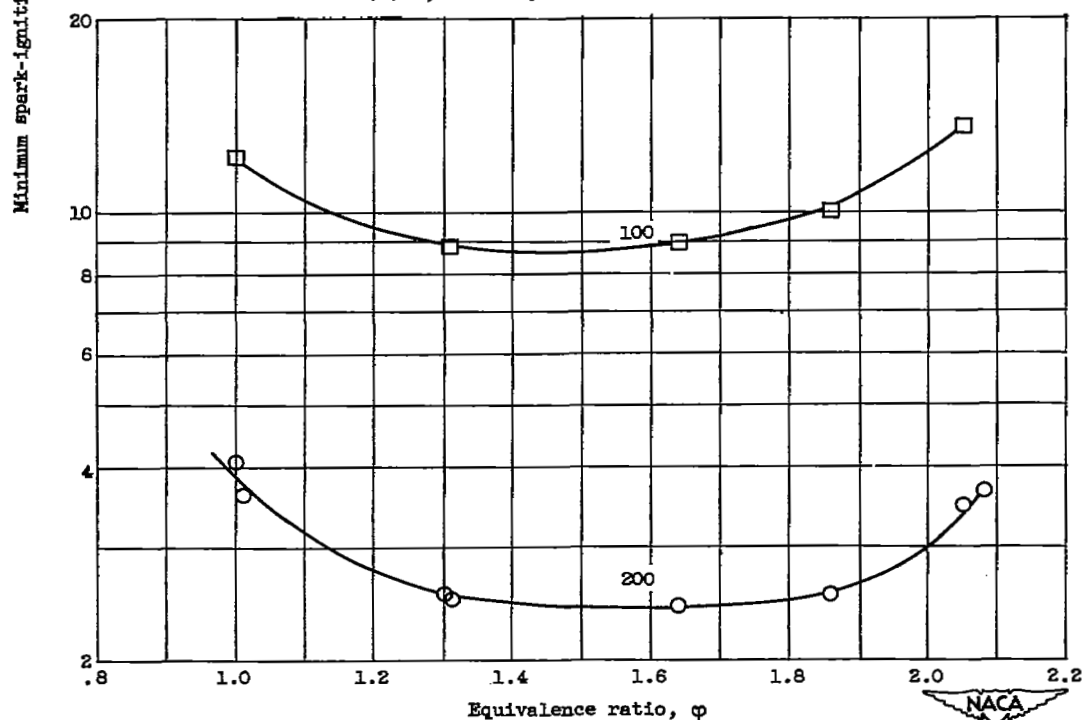


Figure 4. - Minimum spark-ignition energies of paraffins and cycloparaffins at reduced pressures.

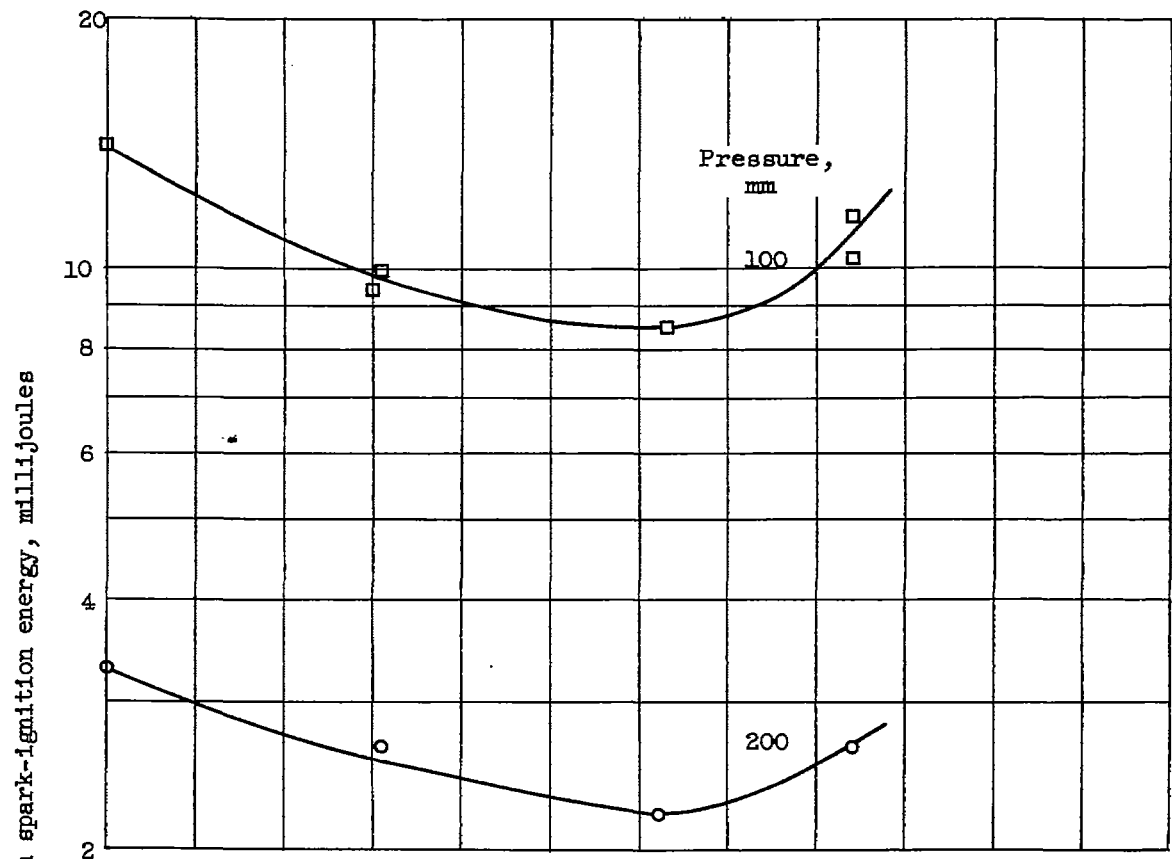


(d) 2,2-Dimethylbutane - air mixtures.

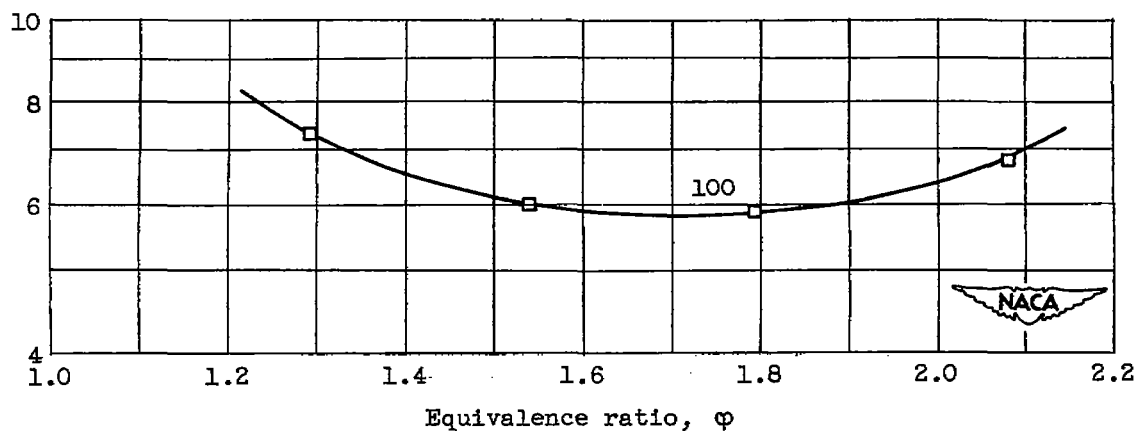


(e) Isopentane-air mixtures.

Figure 4. - Concluded. Minimum spark-ignition energies of paraffins and cyclo-paraffins at reduced pressures.



(a) Pentene-2 - air mixtures.



(b) Acrylonitrile-air mixtures.

Figure 5. - Minimum spark-ignition energies of olefinic fuels at reduced pressures.

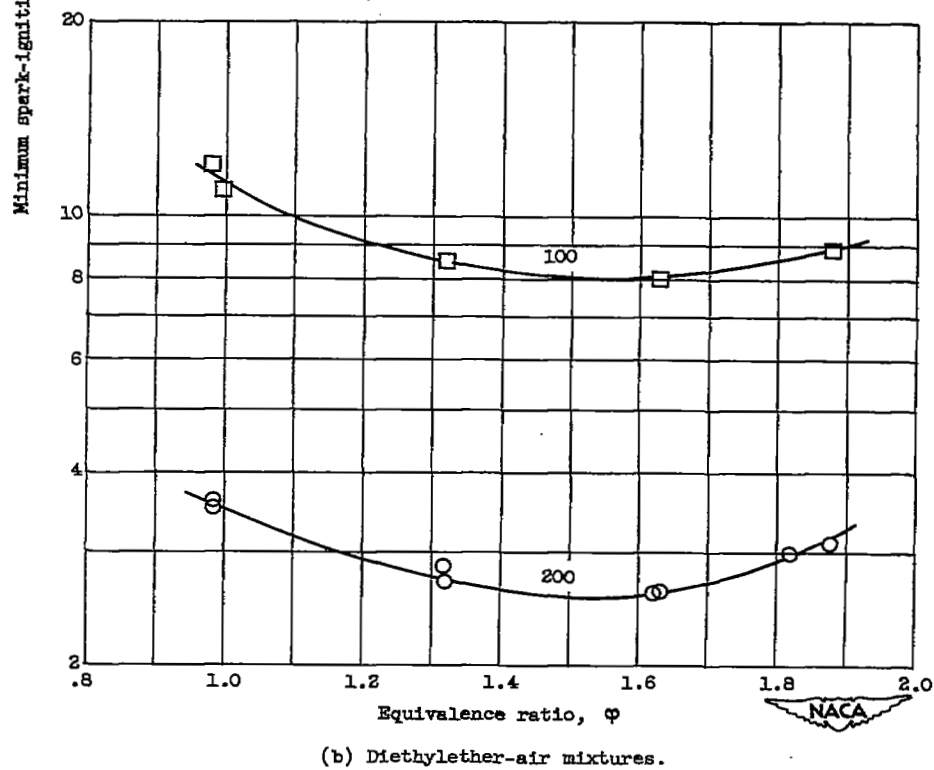
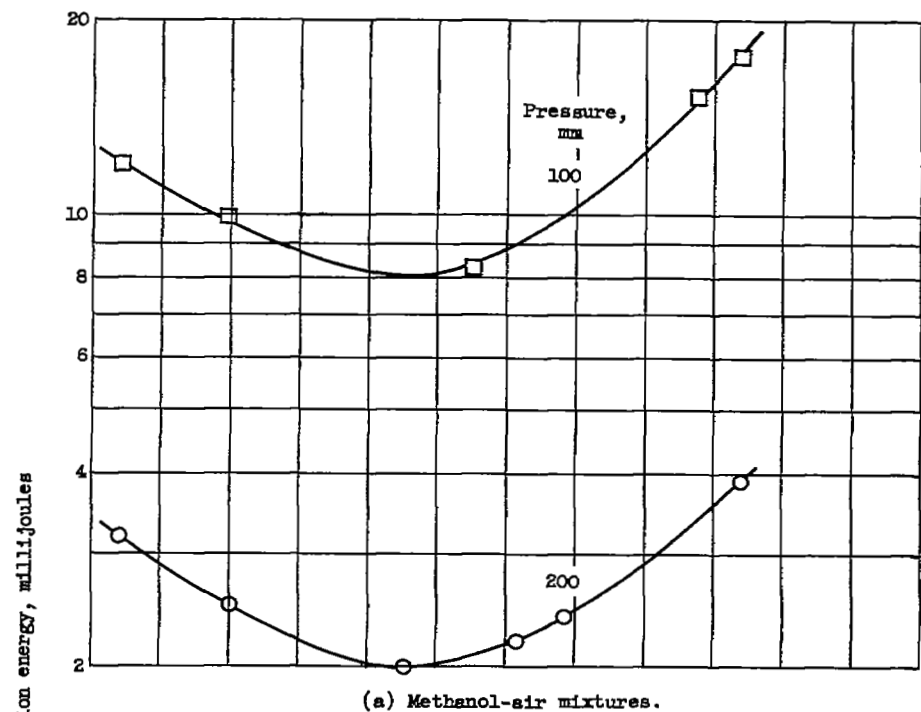
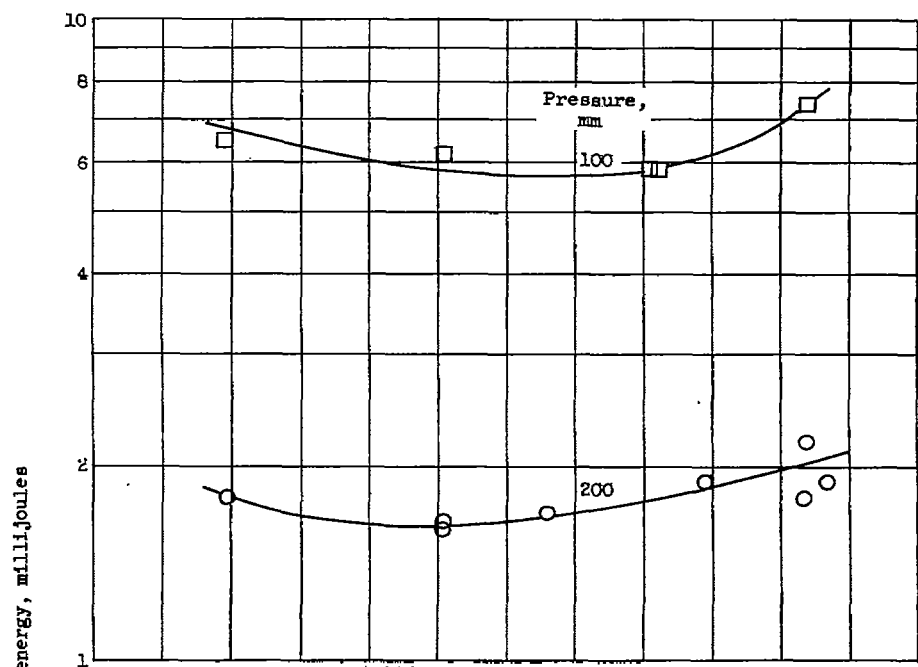
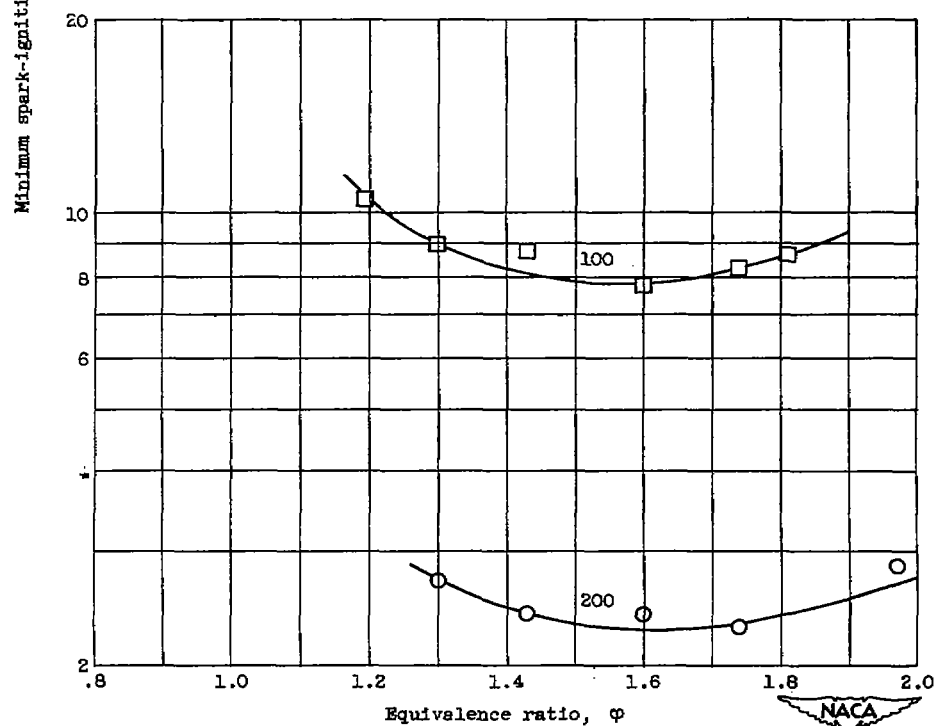


Figure 6. - Minimum spark-ignition energies of oxygenated fuels at reduced pressures.





(c) Propylene oxide - air mixtures.



(d) Tetrahydropyran-air mixtures.

Figure 6. - Concluded. Minimum spark-ignition energies of oxygenated fuels at reduced pressures.

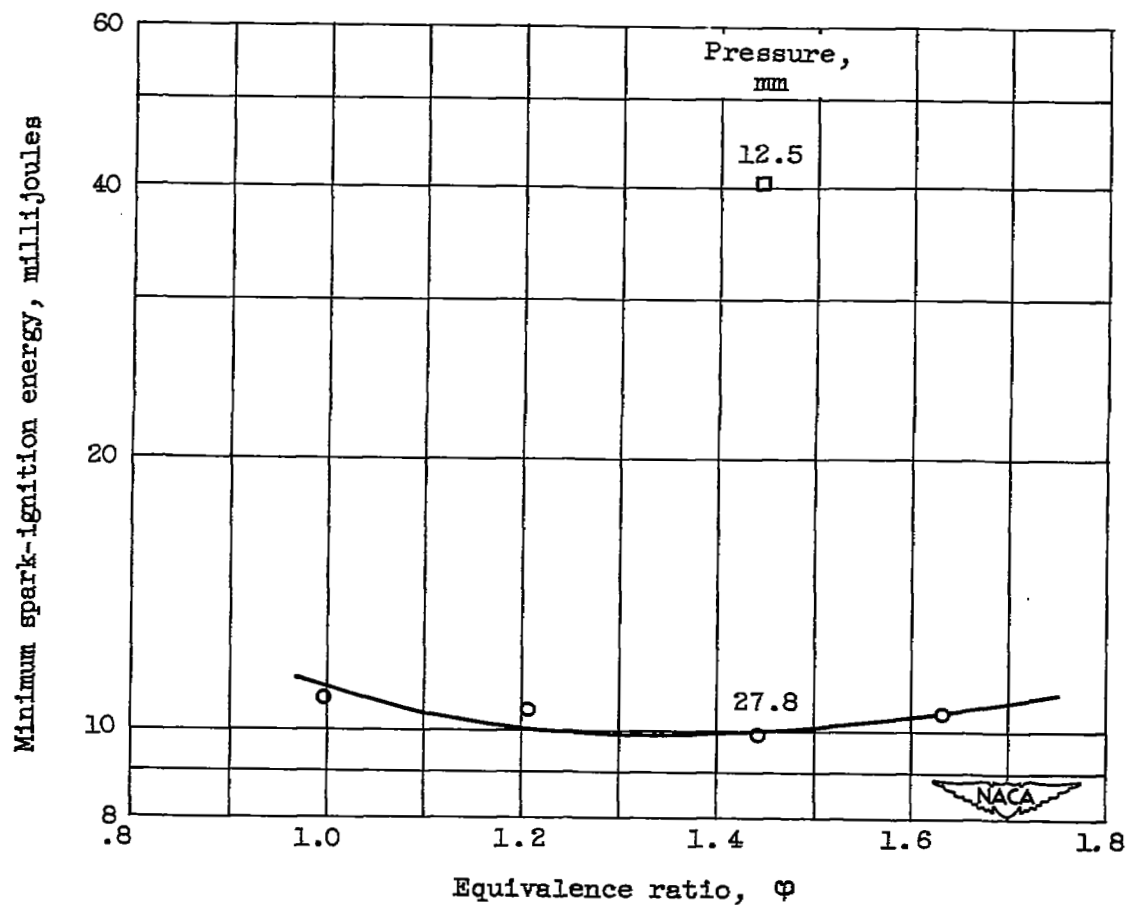


Figure 7. - Minimum spark-ignition energies of carbon disulfide - air mixtures at reduced pressures.

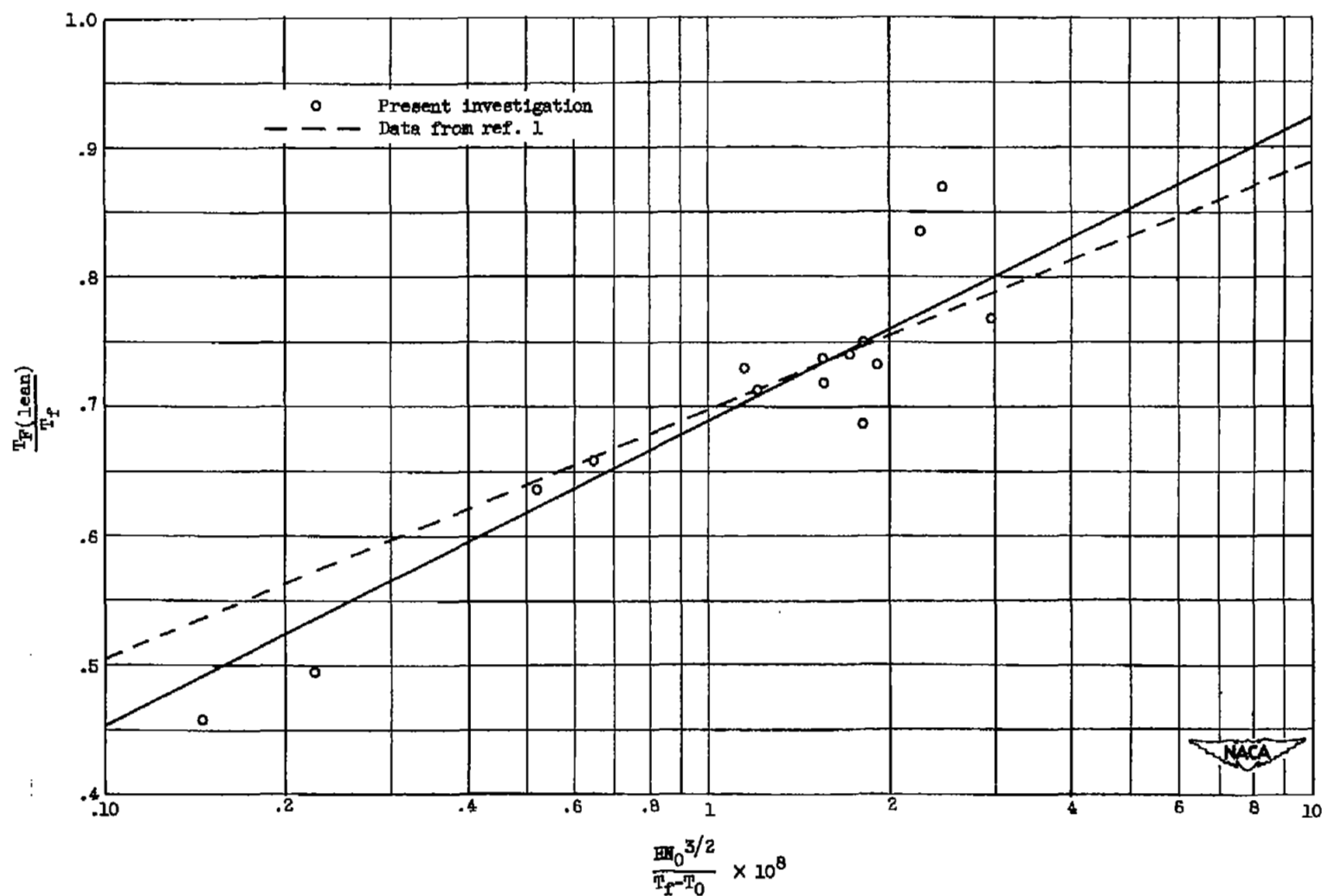


Figure 8. - Experimental data as applied to lean-limit flame-temperature theory of reference 1 for stoichiometric mixtures at 1 atmosphere.

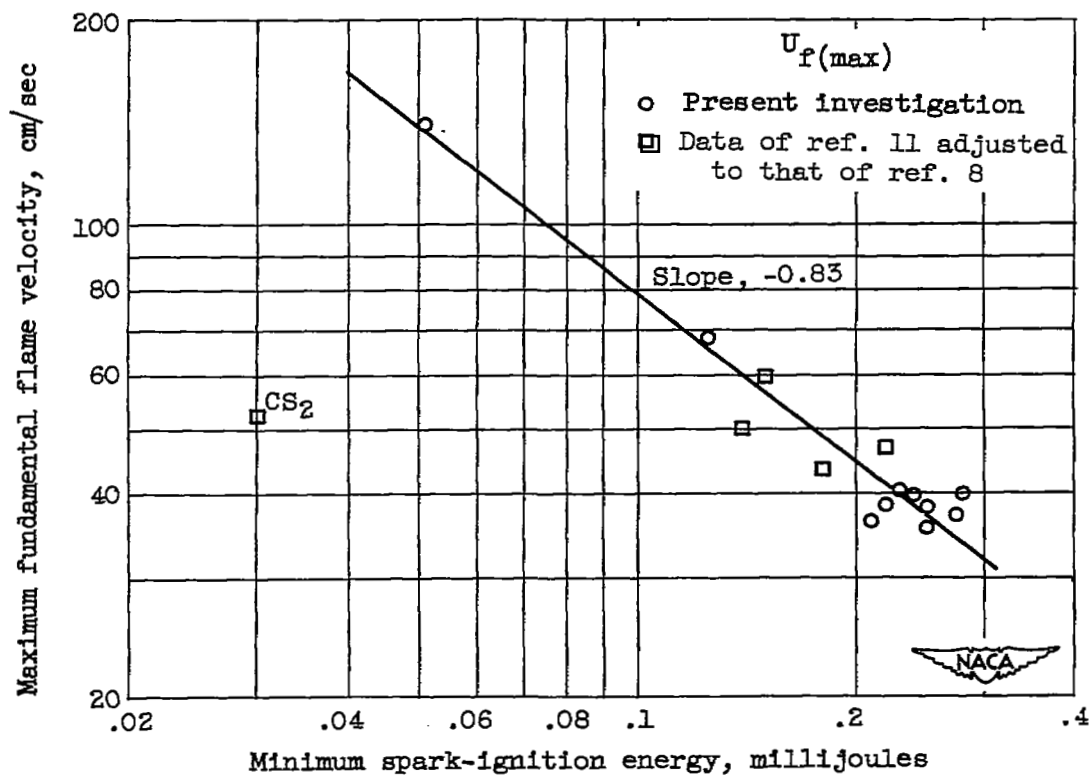


Figure 9. - Relation of maximum fundamental flame velocity to minimum spark-ignition energy at 1 atmosphere.

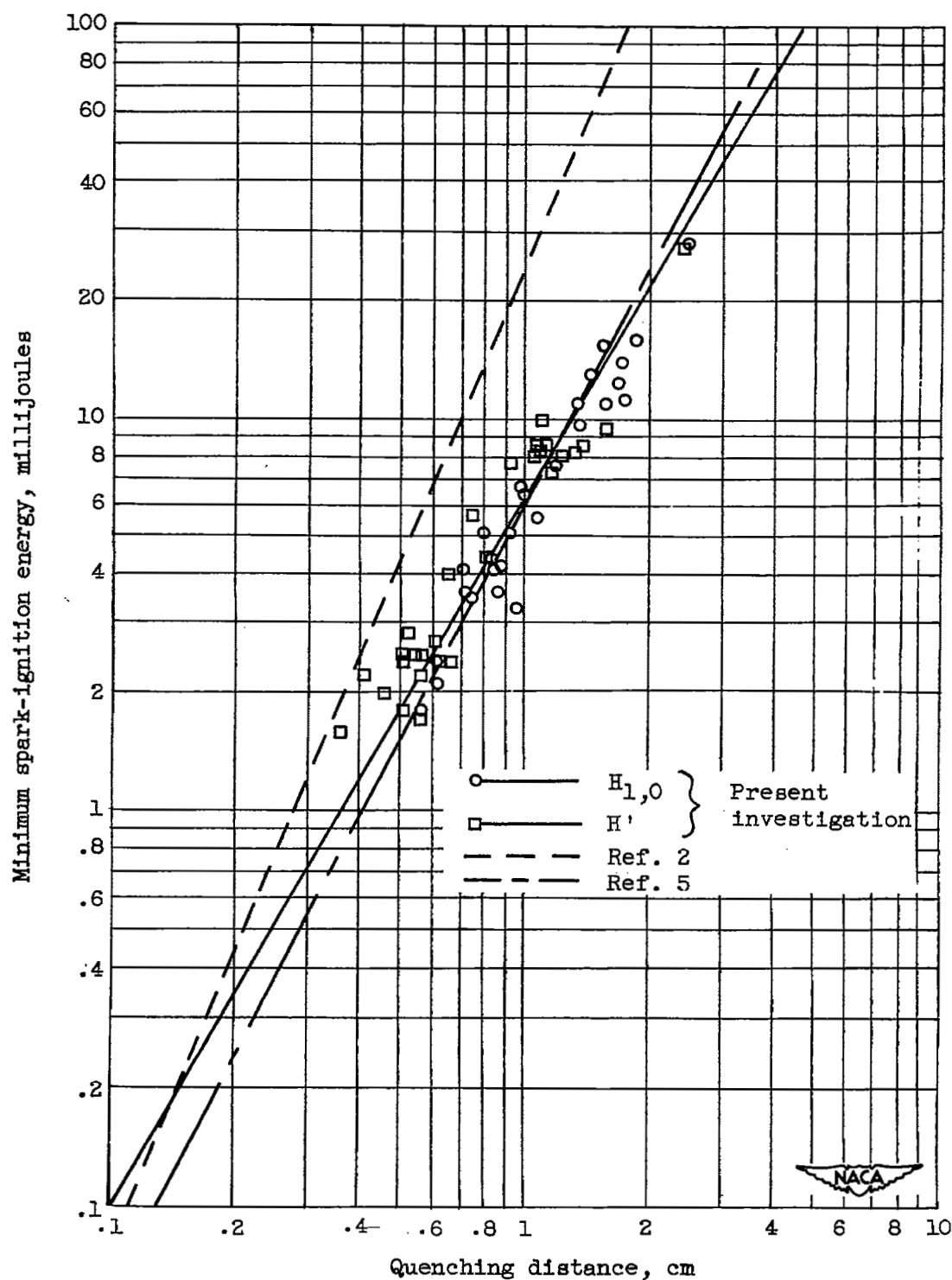


Figure 10 - Minimum spark-ignition energies and quenching distances as compared with data of references 2 and 5.

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